ENERGY LEVELS IN A^{38}
AND Ti^{46} FROM THE p,n
REACTION ON Cl^{37} and Sc^{45}
RESPECTIVELY
by
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and
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Course VIII

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by

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(1951)

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ABSTRACT

The M.I.T. Rockefeller Generator was used as a source of protons for a study of the p,n reaction on Cl^{37} and Sc^{45}. A 1.8 Kev chlorine target and a 5.0 Kev scandium target were used. The Rockefeller Generator was equipped with a proton magnetic moment resonance field control for measuring and controlling the proton energies. A long counter was used for neutron detection, the yield of which showed a number of maxima. The proton kinetic energies at which these maxima occur are tabulated, but are not corrected for the effects due to the thickness and possible surface contamination of the targets, and motion of the center of mass. These values when corrected and combined with the binding energies of a proton in the compound nuclei give the energy levels in the compound nuclei. Energy level spacings, obtained

15655

from the separation of the peaks in the yield curve are also tabulated.

Chlorine was investigated from 1.550 Mev to 2.510 Mev. The observed threshold of 1.641 ± .002 Mev led to a Q value of -1.598 ± .002 Mev and a mass difference for $A^{37} - Cl^{37}$ of .000876 ± .000005 amu. The average energy level spacing in A^{38} was 6.1 Kev.

Scandium was investigated from 2.760 Mev to 3.128 Mev. The observed threshold of 2.913 ± .003 Mev led to a Q value of -2.850 ± .003 Mev and a mass difference for $Ti^{45} - Sc^{45}$ of .002221 ± .000006 amu. The average level spacing in Ti^{46} was 6.0 Kev.

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CHAPTER I

INTRODUCTION

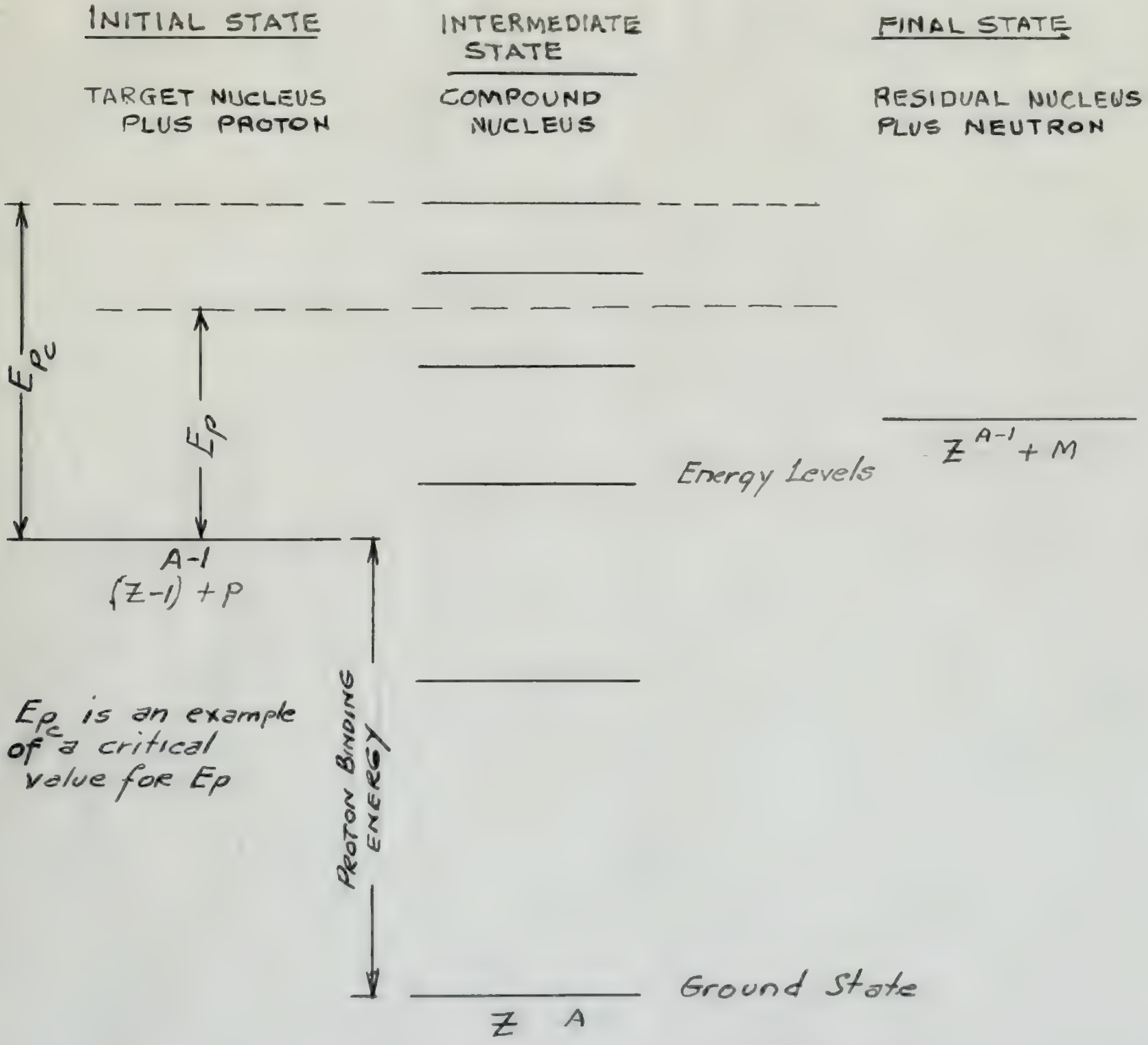
During the nineteenth century, a great deal of work was done on optical spectra and atomic energy levels. From this grew our present day quantum mechanical picture of atomic and molecular structure. The present work on nuclear energy levels is expected to lead to a similar improvement in our knowledge of nuclear structure.

One method of observing nuclear energy levels is by means of the (p,n) reaction:

$$(Z-1)^{A-1} + p \rightarrow Z^{A} \rightarrow Z^{A-1} + n + Q$$

It is experimentally known that the neutron yields from (p,n) reactions exhibit maxima at certain energies of the bombarding protons. The Breit-Wigner theory attempts to explain this as a resonance phenomenon. When the kinetic energy of the proton (Ep) approaches certain critical values, the total energy of the initial state (target nucleus plus proton) corresponds to the energy levels of the compound nucleus. However, the proton kinetic energies at which maxima in the neutron yields occur differ from these critical values because of the thickness and possible sur-

face contamination of the target, the displacement of the peak due to the effect of neighboring peaks, and motion of the center of mass. By making corrections for these effects, and knowing the binding energy of the proton, the observed proton energies of the maxima lead to energy levels of the compound nucleus. (see diagram)



Although a number of other reactions give the same results, the (p,n) reaction was used for the following reasons. The Rockefeller generator provides a convenient source of protons of good energy resolution. The product particles, neutrons, are easily detected. Since they are uncharged, they have a long range and penetrate the target, which stops all of the bombarding protons. Thus the measured yield is all due to the neutrons as none of the protons get to the counter.

Previous work has been done on energy levels in light nuclei using the (p,n) reaction. A summary of this work is given by Richards et al (R1). The (p,n) reaction in manganese has been studied by McCue and Preston (M1), and in scandium and vanadium by Baker, Howell, Goodman and Preston (B1, B2). The latter used the M.I.T. Rockefeller generator, but a proton resonance system which controls the magnetic field has been installed subsequently. This allows much better resolution of the proton energy, which together with the use of thinner targets, results in much better resolution of the peaks in scandium.

The threshold energies of chlorine and scandium are low enough (1.6 and 2.9 Mev respectively) to permit the use of the Rockefeller generator. Although these are moderately heavy nuclei, their coulomb barriers (5.3 Mev for

chlorine and 6.1 Mev for scandium) are low enough so that satisfactory yields could be obtained. The level spacings of the compound nuclei are sufficient to permit the observation of a fair number of levels under the conditions of this experiment, and targets of these elements are fairly easy to prepare from readily available materials.

CHAPTER II

EXPERIMENTAL ARRANGEMENT

General: The Rockefeller generator (W1, J1) is an electrostatic generator which has been adapted as a proton accelerator. The protons of desired energy were bent through 90° by a magnetic field. They then struck the target, which was composed of a layer of the desired element on a tantalum backing. The resulting neutrons were then detected by a BF_3 proportional counter, surrounded by paraffin. After amplification, the pulses were counted on a scaler.

Proton Energy: The proton energy was determined from the intensity of the magnetic field, measured by the "proton resonance method," which is described by Madden (M3). The fundamental non-relativistic equations dealing with this measurement are given below.

The expression for the force on a charged particle moving in a magnetic field is:

$$\frac{mv^2}{r} = \frac{Bev}{c}$$

$$v = \frac{reB}{cm}$$

$$E = \frac{1}{2}mv^2 = \frac{1}{2}m\left(\frac{re}{cm}\right)^2 B^2 = k'B^2$$

$$E = k'B^2$$

m = mass of proton
v = velocity of proton
r = radius of curvature
B = magnetic field
c = velocity of light

The expression for the torque exerted by a magnetic field on a body of magnetic moment μ is:

$$T = B\mu \sin\theta$$

also;

$$T = \frac{dp}{dt} = \frac{\mu}{\gamma} \sin\theta\,(2\pi f)$$

$$\gamma B = 2\pi f$$

$$E = kf^2$$

e = charge on electron

E = energy of proton

T = torque

μ = magnetic moment of proton

θ = angle between μ (or I) and B

p = angular momentum of proton

f = frequency of precession of proton in magnetic field

γ = gyromagnetic ratio of a proton $= \frac{\mu}{I}$

I = proton angular momentum

k = constant

k' = constant

Therefore, the energy of the protons is proportional to the square of the frequency, which is measured with a frequency meter. For the determination of the proportionality constant, k, which relates proton energy to frequency, the Li^7 threshold (E_o = 1.8822 Mev as measured by Herb (H1, H2)) was used. The frequency corresponding to this E_o is f_o = 10.485 mc. Therefore,

$$E_o = kf_o^2$$

$$k = E_o/f_o^2 = \frac{1.8822}{(10.485)^2} = 0.017121 \text{ Mev/(mc)}^2$$

$$= 17.121 \text{ kev/(mc)}^2$$

This value of k was used in the present work. Substantial changes in k result from readjustments of the proton resonance apparatus. In addition, there are minor variations in k as discussed below.

The accuracy of the measured value of the energy of the beam is limited because of the following:

1. A possible variation of the value of k with energy. This has been studied by Preston and Stelson (P1) using the mass 1 and 2 beams on a (p,γ) resonance in aluminum at 993 Kev. The error was found to be less than 1 part in 5,000 in the absolute value of the beam energy.

2. The frequency can be measured to 1 part in 100,000, and since the energy is proportional to the square of the frequency, this causes an error of 2 parts in 100,000 in the value of the beam energy.

3. The width of the beam-defining slits could permit a maximum error of 15 parts in 10,000 in the beam energy, for 40 mil slits, and 7.5 parts in 10,000 for 20 mil slits. The actual error is probably less than half of these. This was determined by Preston and Stelson (P1).

4. The value of k is determined from the (p,n) threshold of Li^7 (H1, H2), and this causes an error of 1 part in 1000 in the beam energy because of the uncertainty in the Li^7 threshold.

5. A drift in the value of k since the last calibration, using the Li^7 threshold, may cause an error of 1 part in 2000 in the beam energy. The reason for this drift is unknown.

6. The use of the non-relativistic equation introduces an error. The calibration is such that this error is zero at E_0. According to Preston (72) the error is about 1.7 Kev at a proton energy of 3.1 Mev (the highest energy used), and is less for lower energies.

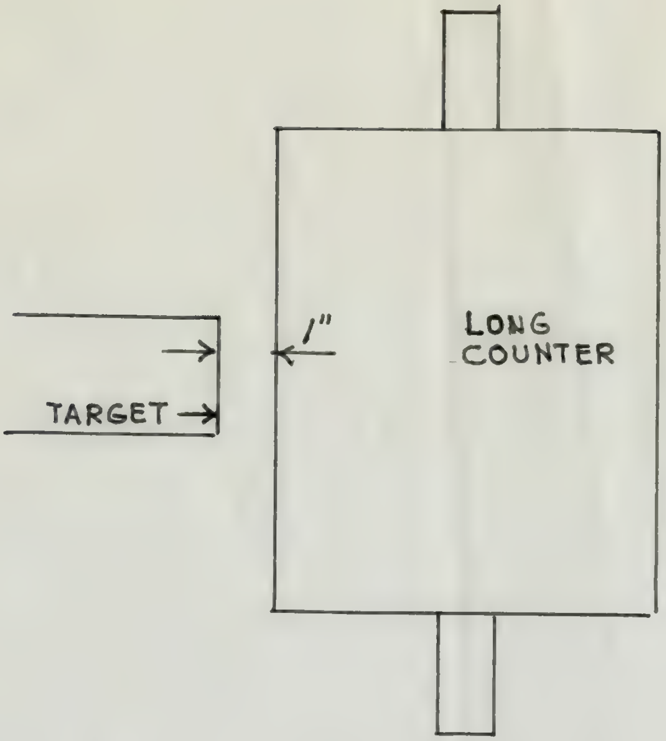
In addition to the above, which cause an uncertainty in the beam energy prior to striking the target, the thickness and surface contamination of the target cause a further uncertainty in the energy of the reacting protons. Because of the care used in the preparation and use of the targets, and the ability to reproduce data, it was assumed that surface contamination was negligible, and did not build up during the experiment. The upper limit to the target thickness, discussed in a later section, sets an upper limit to the uncertainty in the energy of the protons due to this cause. Considering all of these factors, it is estimated that the values of the proton energies, relative to Herb's measured value of the Li^7 (p,n) threshold, are accurate to within 0.1%.

Instrumentation: The long counter used to detect

neutrons consisted of an enriched BF_3 counter tube, surrounded by paraffin, similar to that described by Hansen and McKibben (H4). The paraffin cylinder was 8" in diameter and 10" in length, and was surrounded by cadmium. This counter differed from that of Hansen and McKibben in that no holes were provided in the face of the paraffin. The counter tube had the following specifications:

Outside diameter	1"
Wall Thickness	0.042" of brass
Active volume	10" in length
Center Wire	2 mil tungsten
Filling	55 cm of Hg of 96% enriched $B^{10}F_3$
Operating voltage	2200 volts

The long counter was mounted with the axis of the cylinder perpendicular to the direction of the proton beam as shown in the sketch below. It was used in this position in order to subtend as large a solid angle as possible. Since the neutrons may be emitted anisentropically in the center of mass system, this arrangement reduced the possibility of not detecting peaks in the yield curves because of the angular distribution of the emitted neutrons. It was checked at the start and finish of each individual run with a standard Ra-Be neutron source.



The data on the other instruments used are:

Preamplifier: Laboratory for Nuclear Science and Engineering, M.I.T., Model 100.

Amplifier: Laboratory for Nuclear Science and Engineering, M.I.T., Model 100. The preamplifier and amplifier are discussed fully in Elmore and Sands (El). The amplifier had a gain of 10,000, a rise time of 0.5 micro seconds, and a clipping time of 2 micro seconds.

Scaler: Atomic Instrument Co. Model 105. Resolving time -- 5 micro seconds.

Regulated High Voltage Supply: M.I.T. Servo Lab., Electronic Nuclear Instrument Project. Electronically stabilized.

Frequency Meter: General Radio Co. Model 271. 160 kc -- 15 mc.

The amplifier, preamplifier, and high voltage supply were run from a voltage regulating transformer with a sine wave output.

CHAPTER III

TARGETS

The scandium targets were made from Sc_2O_3 prepared by Johnson and Malthey and Co., Ltd. of London. It was obtained from the Jarrell Ash Co. of Boston, Massachusetts. The oxide was certified "spectrographically standardized." Baird Associates of Cambridge, Massachusetts made the targets using the method developed by Baker and Howell (B2). The scandium targets were not thicker than 5 Kev. This upper limit was determined from the width of the narrowest peak measured at half its maximum amplitude. A target used by Baker et al was available, but almost no yield of neutrons was obtained from this target. Apparently the targets deteriorate over a period of time, so that targets used in this work were made very shortly before being used. Between runs they were stored in a vacuum to minimize any contamination or oxidation. While being bombarded with protons, the targets were continuously cooled by a stream of air to reduce evaporation of the scandium. In order to ensure that no changes took place in the target during a run, a measurement of the same peak was made at the start and finish of each individual run. Using these methods, no difficulties were encountered with the targets.

The chlorine targets were made from NaCl, prepared by Johnson and Matthey and Co. Ltd. of London. It was obtained from the Jarrell Ash Co. of Boston, Massachusetts. The NaCl was of a high degree of purity, and was certified "spectrographically standardized." Lines of silver, copper, and magnesium were faintly visible. Lines of calcium were very faintly visible. Iron and silicon lines were detected, but were fainter than those seen using plain electrodes, so their presence is doubtful. The above is from the report on the NaCl issued by the Johnson and Matthey Co.

Baird Associates of Cambridge, Massachusetts made the chlorine targets, using the method described by Baker and Ewall (28) for the preparation of vanadium targets. The threshold energies of Na (pn) and Cl^{35} (pn) were well above the energies used, so that they did not enter into the reaction. The target used for the energy level measurements in the chlorine work was not thicker than 1.8 kev. The target used near threshold was not thicker than 1.3 kev. At first, difficulty was experienced with the chlorine targets changing during a run. When checking a peak at the end of a run, its maximum amplitude would be much less than it had been at the start of the run. However, by keeping the beam current below 3 micro amperes, and using a spray of cooling water on the target, in addition to taking the precautions

described for the scandium targets, this difficulty was overcome.

It was assumed that effects due to surface contaminations on the chlorine and scandium targets were negligible. This assumption is based on the method used to make the targets, the fact that they were stored in vacuum in between runs, and the ability to reproduce data.

CHAPTER IV

EXPERIMENTAL RESULTS

$Cl^{37}(p,n)A^{37}$: The neutron yield from the chlorine target was measured over an energy range from 1.550 Mev to 2.510 Mev.

From 1.550 Mev to 1.641 Mev, the neutron yield observed was constant at a background of 0.1. As the proton energy was increased, the neutron yield started to increase. This increase occurred just above the threshold of the reaction. Figure 1 shows a plot of the results near the threshold, from 1.630 Mev to 1.700 Mev. The region from 1.550 Mev to 1.630 Mev is not shown in this figure, since the yield was a constant as previously mentioned. The threshold[1] for the reaction was taken as the energy at which the rise in the yield curve started, or a value of 1.641 ± 0.002 Mev. This error is due to the 0.1% uncertainty in the proton energy, as previously discussed. This value agrees very closely with 1.640 ± 0.004 Mev as measured by Richards et al (R1).

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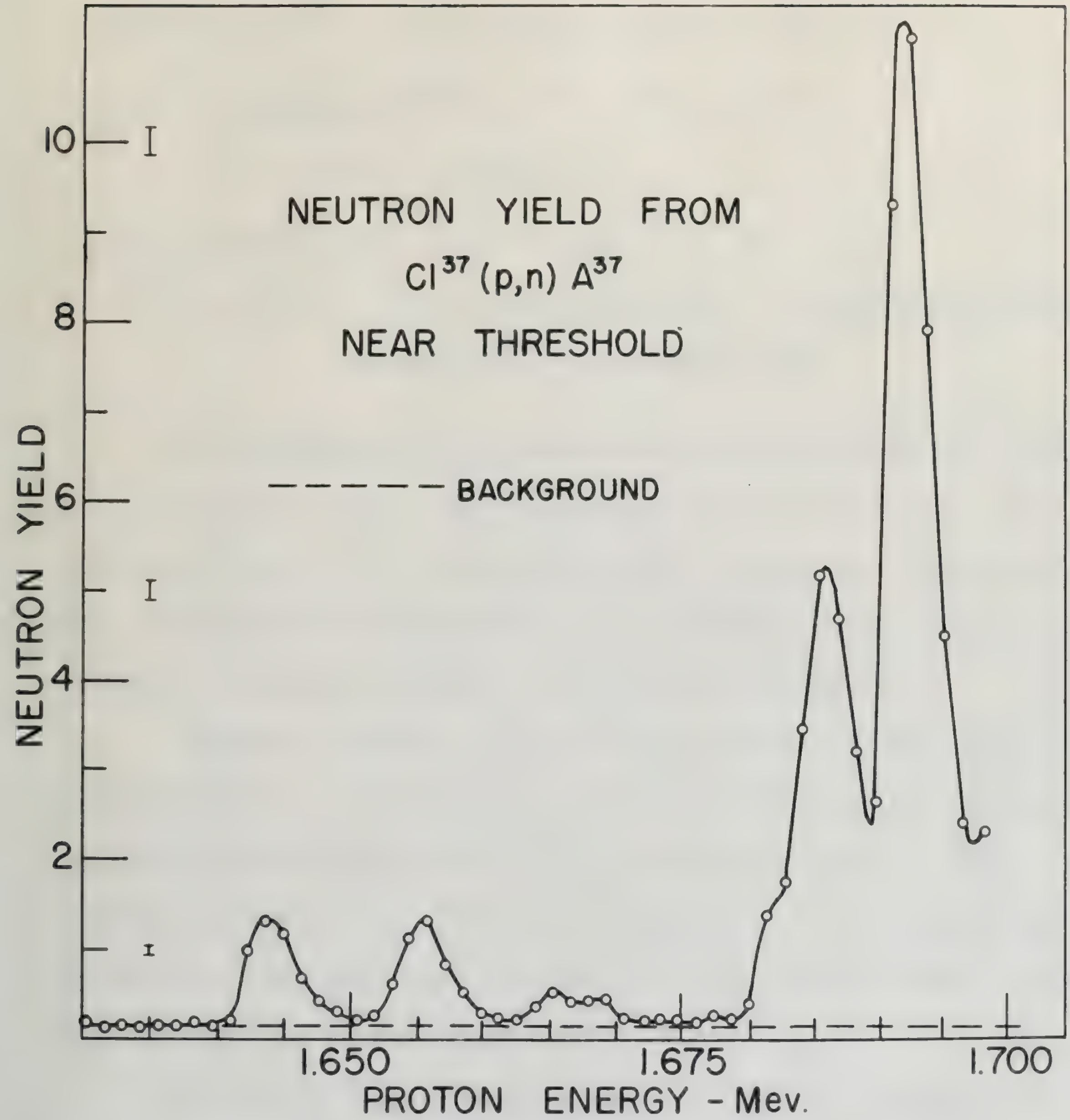
[1] For neutrons emitted at 0° with respect to the direction of incident protons.

Figure 1

NEUTRON YIELD FROM $Cl^{37}(p,n)A^{37}$

NEAR THRESHOLD


NEUTRON YIELD FROM
$Cl^{37}(p,n)A^{37}$
NEAR THRESHOLD
BACKGROUND
NEUTRON YIELD
10
8
6
4
2
1.650
1.675
1.700
PROTON ENERGY - Mev.

$$Cl^{37}(p,n)A^{37} \qquad \text{threshold} = 1641 \pm 2 \text{ Kev}$$

$$-Q = \frac{36.9775}{37.9856}(1641 \pm 2) = 1598 \pm 2 \text{ Kev}$$

$$= 0.001716 \pm 0.000002 \text{ amu}$$

$$\text{Mass difference}^{2} \quad (A^{37} - Cl^{37}) = -Q - (n-p)$$

$$(A^{37} - Cl^{37}) = 0.001716 \pm 0.000002 - (0.000840 \pm 0.000005)^{(B3)}$$

$$= 0.000876 \pm 0.000005 \text{ amu}$$

The background was determined by measuring the counting rate obtained when a pure tantalum target was used. It is shown on Figure 1. The experimental points are shown by the circles. The magnitude of the probable error in these points is indicated along the axis of ordinates.

Figure 2 shows a plot of the results from 1.670 Mev to 2.510 Mev. The background was omitted from this curve because it was negligible. The probable error at high yields is indicated, but at low yields it is too small to be shown. For the sake of clarity, the experimental points are not indicated on Figure 2.

Figure 3, the region from 2.375 Mev to 2.510 Mev, plotted to a larger scale, shows experimental points. The probable error of these points is less than the size of the circles indicating the points. This plot is included to

---

[2] The effect of the electron binding energies was neglected as they were of the order of electron volts, whereas the uncertainty in the value of Q is of the order of Kev.

Figure 2

NEUTRON YIELD FROM $Cl^{37}(p,n)A^{37}$

1.670 - 2.510 Mev.

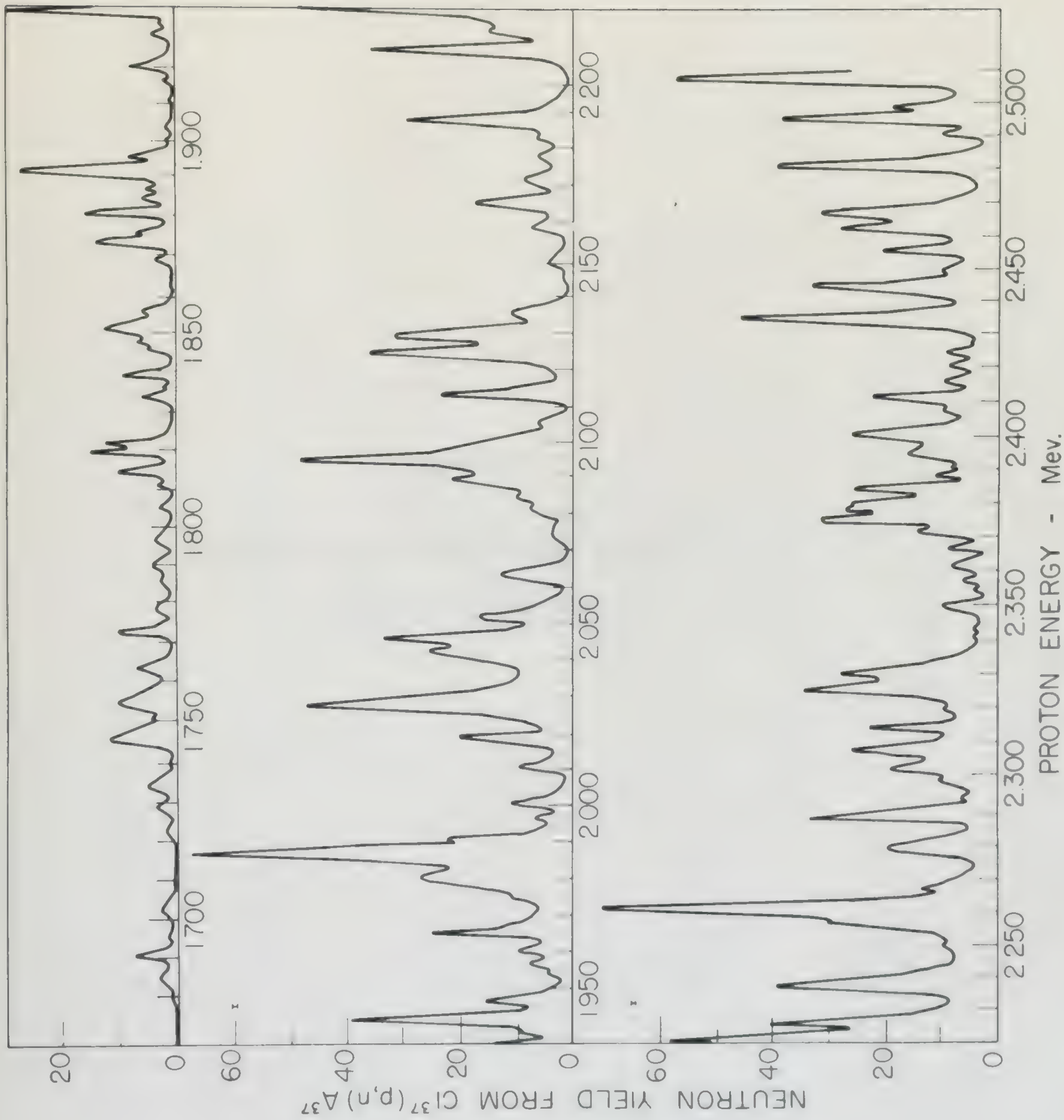
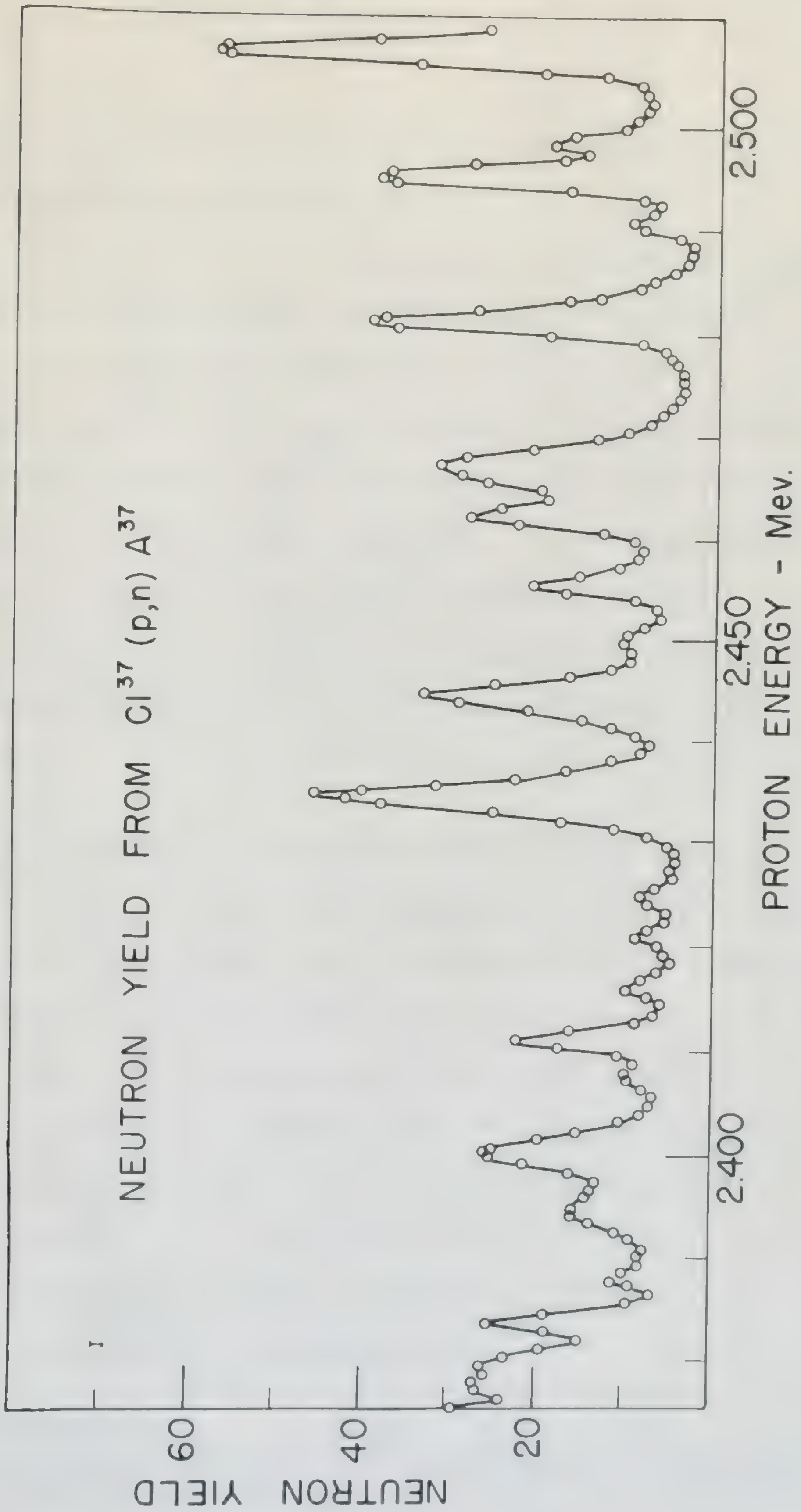

NEUTRON YIELD FROM Cl^{37}(p,n)A^{37}
PROTON ENERGY - Mev.
20
0
60
40
20
0
60
40
20
0
1700
1750
1800
1850
1900
1950
2000
2050
2100
2150
2200
2250
2.300
2.350
2.400
2.450
2.500

Figure 3

NEUTRON YIELD FROM $Cl^{37}(p,n)A^{37}$

2.375 - 2.510 Mev.


NEUTRON YIELD FROM Cl^{37} (p,n) A^{37}
NEUTRON YIELD
60
40
20
PROTON ENERGY - Mev.
2.400
2.450
2.500

show the spacing of the points, and is typical of the entire energy region investigated.

Table 1 lists all of the peaks in the neutron yield. The narrowest peak found, at 1.839 Mev, had a width of 1.8 Kev at half its maximum amplitude. This width was due to the energy spread, the target thickness, and the actual width of the level. Thus this value of 1.8 Kev sets an upper limit to the target thickness. The target thickness, measured in Kev, decreases with increasing energy. If the energy spread remains constant, the greater width of other peaks would be due to an actual increase in the width of the levels.

$Sc^{45}(p,n)Ti^{45}$: From 2.760 Mev to 2.913 Mev, the yield from the scandium target was practically constant, varying from 2.3 to 3.0 ± 0.07. At 2.913 Mev the yield rose sharply, indicating that the threshold[3] for the reaction is at 2.913 ± 0.003 Mev. This agrees fairly well with the value of 2.85 Mev obtained by Taschek (T1). A plot of the results from 2.894 Mev to 3.128 Mev is shown in Figure 4.

$$Sc^{45}(p,n)Ti^{45} \qquad \text{threshold} = 2913 \pm 3 \text{ Kev}$$

$$-Q = \frac{44.966}{45.974}(2913 \pm 3) = 2850 \pm 3 \text{ Kev}$$

$$= 0.003061 \pm 0.000003 \text{ amu}$$

---

[3] For neutrons emitted at 0° with respect to direction of incident protons.

Figure 4

NEUTRON YIELD FROM $Sc^{45}(p,n)Ti^{45}$

2.894 - 3.128 Mev.

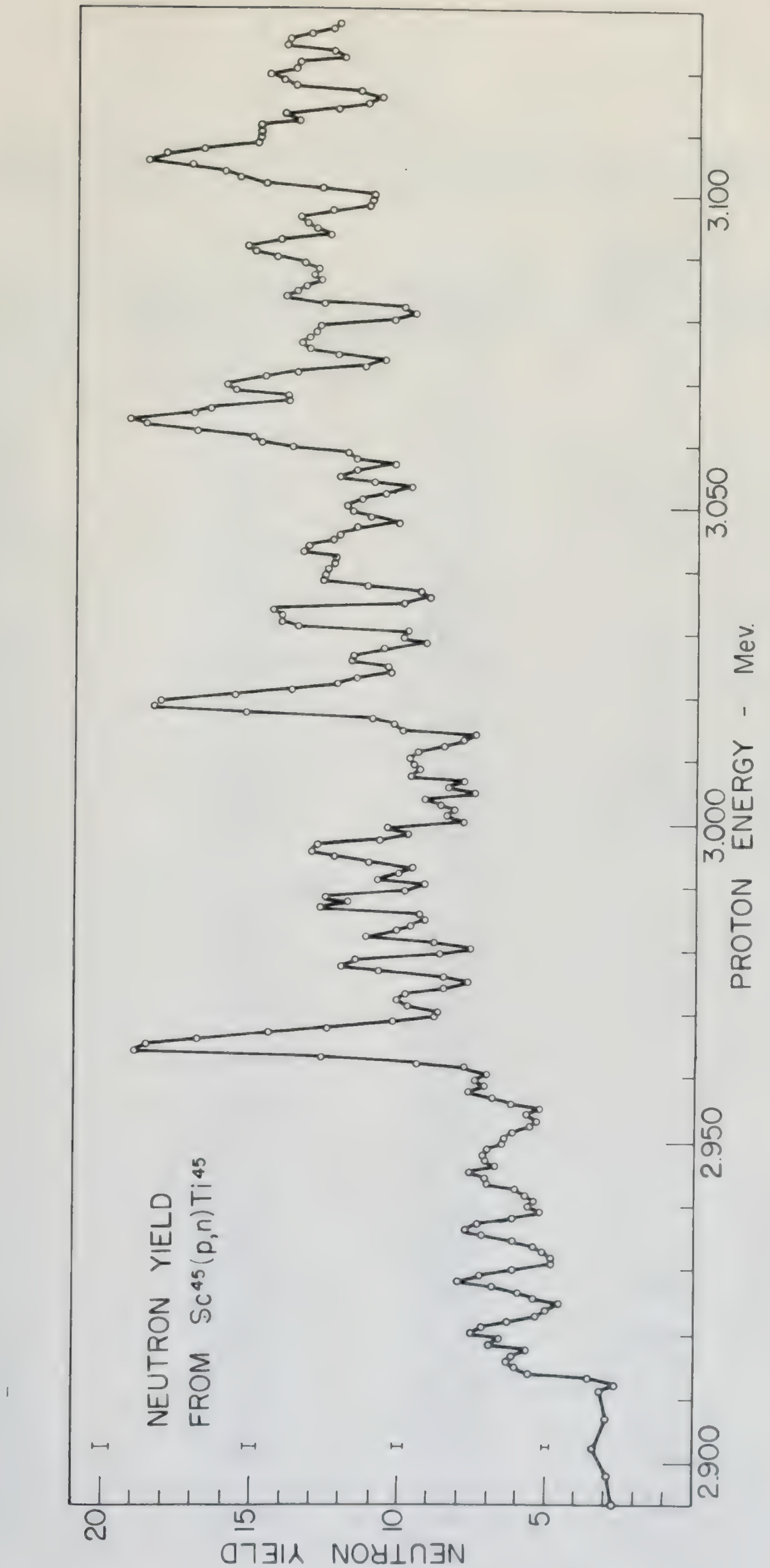

NEUTRON YIELD
FROM Sc⁴⁵(p,n)Ti⁴⁵
NEUTRON YIELD
20
15
10
5
2.900
2.950
3.000
3.050
3.100
PROTON ENERGY - Mev.

TABLE 1
RESONANCE PEAKS IN NEUTRON YIELD FROM $Cl^{37}(p,n)A^{37}$
Error in E$\pm$ 0.1%, relative to $Li^{7}(p,n)$ threshold

Frequency of peak - mc.	Energy of peak - Mev.	Amplitude of peak	Width at half max. - kev.	Separation from next peak - kev.
Thick target - near threshold:				
9.800	1.644	1.3	4.3	11
9.831	1.655	1.3	4.3	11
9.860	1.666	0.5		3
9.871	1.669	0.4		9
9.897	1.678	0.25		4
9.910	1.682	1.5		4
9.922	1.686	5.3	5.0	6
9.939	1.692	11.3	4.4	
Thin target - entire range:				
9.799	1.644	1.0		11
9.834	1.655	1.0		11
9.864	1.666	0.5		3
9.873	1.669	0.5		9
9.900	1.678	0.2		4
9.912	1.682	1.2		4
9.924	1.686	3.5	4.9	5
9.940	1.691	7.5	1.8	5
9.954	1.696	2.0		7
9.973	1.703	3.2	4.1	19
10.030	1.722	2.0	4.7	7

TABLE 1 (continued)

Frequency of peak - mc.	Energy of peak - Mev.	Amplitude of peak	Width at half max. - Kev.	Separation from next peak - Kev.
10.050	1.729	3.5	3.6	5
10.064	1.734	5.5	4.0	7
10.084	1.741	1.5		5
10.099	1.746	12.5	4.3	5
10.115	1.751	5.0		4
10.126	1.755	10.5	5.1	9
10.151	1.764	7.0	3.2	9
10.177	1.773	10.5	2.3	5
10.192	1.778	4.2	4.1	8
10.213	1.786	3.2		3
10.224	1.789	4.6		7
10.243	1.796	4.4	4.3	9
10.267	1.805	3.5	2.3	5
10.283	1.810	4.3		4
10.293	1.814	11.0	2.7	5
10.307	1.819	15.5		2
10.313	1.821	12.5		12
10.348	1.833	7.0		3
10.355	1.836	2.5		3
10.363	1.839	10.0	1.8	7
10.383	1.846	5.5		2

TABLE 1 (continued)

Frequency of peak - mc.	Energy of peak - Mev.	Amplitude of peak	Width at half max. - Kev.	Separation from next peak - Kev.
10.389	1.848	7.2		3
10.398	1.851	13.0	4.1	4
10.410	1.855	6.5		7
10.430	1.862	1.5		7
10.448	1.869	4.3	3.1	4
10.460	1.873	14.0	2.2	3
10.467	1.876	7.5		5
10.481	1.881	17.0	2.2	4
10.493	1.885	6.5		2
10.499	1.887	6.2		5
10.512	1.892	27.5	3.2	4
10.523	1.896	8.5		4
10.535	1.900	2.0		3
10.544	1.903	2.5		7
10.564	1.910	2.5		6
10.578	1.916	3.0		3
10.588	1.919	9.0	2.9	9
10.612	1.928	4.7		3
10.621	1.931	3.5		3
10.628	1.934	30.5	2.0	4
10.640	1.938	9.5		4

TABLE 1 (continued)

Frequency of peak - mc.	Energy of peak - Mev.	Amplitude of peak	Width at half max. - Kev.	Separation from next peak - Kev.
10.649	1.942	40.0	2.3	5
10.664	1.947	15.5		8
10.685	1.955	4.5		2
10.691	1.957	8.2		4
10.701	1.961	10.2		4
10.714	1.965	25.0	2.9	11
10.742	1.976	11.8		5
10.756	1.981	27.5		6
10.772	1.987	67.5	4.2	4
10.784	1.991	23.0		6
10.800	1.997	7.0		4
10.810	2.001	11.5	3.3	10
10.838	2.011	9.5	3.4	8
10.858	2.019	20.5	3.2	8
10.881	2.027	47.5	4.5	16
10.923	2.043	26.0		3
10.932	2.046	34.5		6
10.948	2.052	17.5	4.3	12
10.980	2.064	13.0	3.9	13
11.013	2.077	3.5		5

TABLE 1 (continued)

Frequency of peak - mc.	Energy of peak - Mev.	Amplitude of peak	Width at half max. - Kev.	Separation from next peak - Kev.
11.026	2.082	7.5		3
11.034	2.085	10.0		5
11.048	2.090	21.0		5
11.061	2.095	49.0	4.4	11
11.090	2.106	6.5		7
11.110	2.113	23.5	3.1	12
11.141	2.125	35.5	4.3	5
11.154	2.130	31.5		6
11.170	2.136	11.0		11
11.199	2.147	2.5		3
11.206	2.150	4.5	4.7	10
11.233	2.160	7.2		7
11.250	2.167	17.0	4.2	7
11.268	2.174	9.5	5.1	7
11.286	2.181	6.5		5
11.300	2.186	7.2		4
11.310	2.190	29.5	3.5	20
11.362	2.210	36.0	3.2	6
11.375	2.216	14.5		7
11.394	2.223	58.0	5.1	5
11.406	2.228	40.5		10

TABLE 1 (continued)

Frequency of peak - mc.	Energy of peak - Mev.	Amplitude of peak	Width at half max. - Kev.	Separation from next peak - Kev.
11.433	2.238	40.0	4.4	12
11.464	2.250	10.0		7
11.482	2.257	31.0		4
11.491	2.261	70.5	4.4	6
11.506	2.267	13.5		12
11.537	2.279	20.5	5.5	9
11.559	2.288	34.0	3.4	5
11.572	2.293	6.0		6
11.586	2.299	11.0		3
11.595	2.302	19.0		5
11.608	2.307	26.5	4.6	7
11.624	2.314	23.0	2.5	6
11.639	2.320	10.0		5
11.652	2.325	34.5		5
11.665	2.330	28.5		11
11.692	2.341	4.5		3
11.700	2.344	4.0		6
11.715	2.350	10.5	4.3	4
11.726	2.354	5.0		4
11.734	2.358	6.0		4
11.745	2.362	8.5	4.8	5

TABLE 1 (continued)

Frequency of peak - mc.	Energy of peak - Mev.	Amplitude of peak	Width at half max. - Kev.	Separation from next peak - Kev.
11.757	2.367	9.5	2.8	5
11.770	2.372	14.5		3
11.777	2.375	32.0		3
11.785	2.378	27.5		2
11.789	2.380	26.0		4
11.800	2.384	25.5		4
11.810	2.388	11.5		3
11.817	2.391	8.0		4
11.827	2.395	16.5		6
11.841	2.401	26.0		7
11.859	2.408	10.0		4
11.868	2.412	22.5	3.0	5
11.880	2.417	10.0		5
11.892	2.422	9.0		4
11.902	2.426	8.5		2
11.908	2.428	5.0		8
11.926	2.436	45.5	3.8	9
11.950	2.445	33.0	3.9	6
11.963	2.451	10.5		5
11.976	2.456	20.5	3.5	7

TABLE 1 (continued)

Frequency of peak - Mc.	Energy of peak - Mev.	Amplitude of peak	Width at half max. - Kev.	Separation from next peak - Kev.
11.992	2.463	28.0		5
12.004	2.468	31.5		13
12.038	2.481	40.0	3.3	10
12.061	2.491	10.5		5
12.072	2.496	38.5	3.3	3
12.080	2.499	19.0		9
12.102	2.508	57.0	3.8	-

Mass Difference[4] $(\mathrm{Ti}^{45} - \mathrm{Sc}^{45}) = - Q - (n-p)$

$= (0.003061 \pm 0.000003) - (0.000840 \pm 0.000005)$ (B3)

$= 0.002221 \pm 0.000006$ amu

The background was not measured over the energy range covered, because of changes made on the generator before this could be done. However, the background in the region of 2.5 Mev was measured, and was substantially the same as the yield obtained below threshold. The experimental points are shown by circles. The magnitude of the probable error in these points is indicated along the axis of ordinates. The experimental points are connected by straight lines, for reasons discussed below.

Table 2 lists all of the peaks in the neutron yield. The narrowest peak found, at 2.929 Mev had a width of 5 Kev at half its maximum amplitude. This sets an upper limit of 5 Kev to the target thickness. The resolution of the peaks was not considered good enough to justify fairing in a smooth curve through the experimental points. Therefore, the points were connected by straight lines to avoid obscuring any details. It is believed that better resolution could be obtained by the use of a thinner target, as in the chlorine experiment.

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[4] See footnote 2 on page 18.

TABLE 2
RESONANCE PEAKS IN NEUTRON YIELD FROM $Sc^{45}(p,n)Ti^{45}$
Error in E ± 0.1%, relative to $Li^{7}(p,n)$ threshold

Frequency of peak - mc.	Energy of peak - Mev.	Amplitude of peak	Width at half max. - Kev.	Separation from next peak - Kev.
13.050	2.916	6.4		4
13.059	2.920	7.5		9
13.078	2.929	8.0	4.6	8
13.096	2.937	7.8	5.7	9
13.116	2.946	7.6		2
13.122	2.948	7.1		11
13.146	2.959	7.7		5
13.159	2.964	19.0	5.5	9
13.176	2.973	10.1		5
13.188	2.978	12.0	5.2	5
13.198	2.983	11.2		5
13.210	2.988	12.8		4
13.218	2.992	10.8		4
13.228	2.996	13.0		8
13.246	3.004	9.2		6
13.259	3.010	9.8		6
13.272	3.016	10.3		3
13.279	3.019	18.4	6.6	8
13.295	3.027	11.7		7
13.310	3.034	14.5		5

TABLE 2 (continued)

Frequency of peak - mc.	Energy of peak - Mev.	Amplitude of peak	Width at half max. - Kev.	Separation from next peak - Kev.
13.322	3.039	12.6		5
13.332	3.044	13.4		7
13.348	3.051	11.9		4
13.358	3.055	12.2		6
13.370	3.061	14.7		3
13.378	3.064	19.3		6
13.390	3.070	16.0		7
13.404	3.077	13.5		7
13.420	3.084	14.0		8
13.438	3.092	15.3		5
13.448	3.097	13.5		6
13.462	3.103	15.6		3
13.468	3.106	18.8		3
13.478	3.109	15.0		11
13.498	3.120	14.6		5
13.508	3.125	14.0		-

General: The yield of neutrons was measured throughout, not as counts per second, but as counts per micro coulomb of the proton beam as determined from a beam current integrator. In this way the counting rate was normalized against any fluctuations in the beam current. Since no correction was made to the counting rate for the efficiency of the long counter, the yield will be distorted at low neutron energies just above the threshold.

The maximum counting rate obtained during either experiment was 14,000 counts per 200 micro coulombs. This corresponds to 3 micro amperes striking the target for 67 seconds. Thus the maximum counting rate was less than 250 counts per second, with an average time between pulses of more than 4,000 micro seconds. The scaler had a resolving time of 5 micro seconds, the amplifier a rise time of 0.5 micro seconds and a clipping time of 2 micro seconds. Since these times were very much less than 4,000 micro seconds, no corrections were necessary in the counting rates.

Figures 5 and 6 show the reproducibility of several peaks, with measurements taken at different times. In order to insure that there had been no appreciable change in target thickness, build up of surface contaminants, or changes in the overall operation of the measuring equipment due to unknown causes, the same peak was measured at

Figure 5

REPRODUCIBILITY OF PEAKS
$Cl^{37}(p,n)A^{37}$

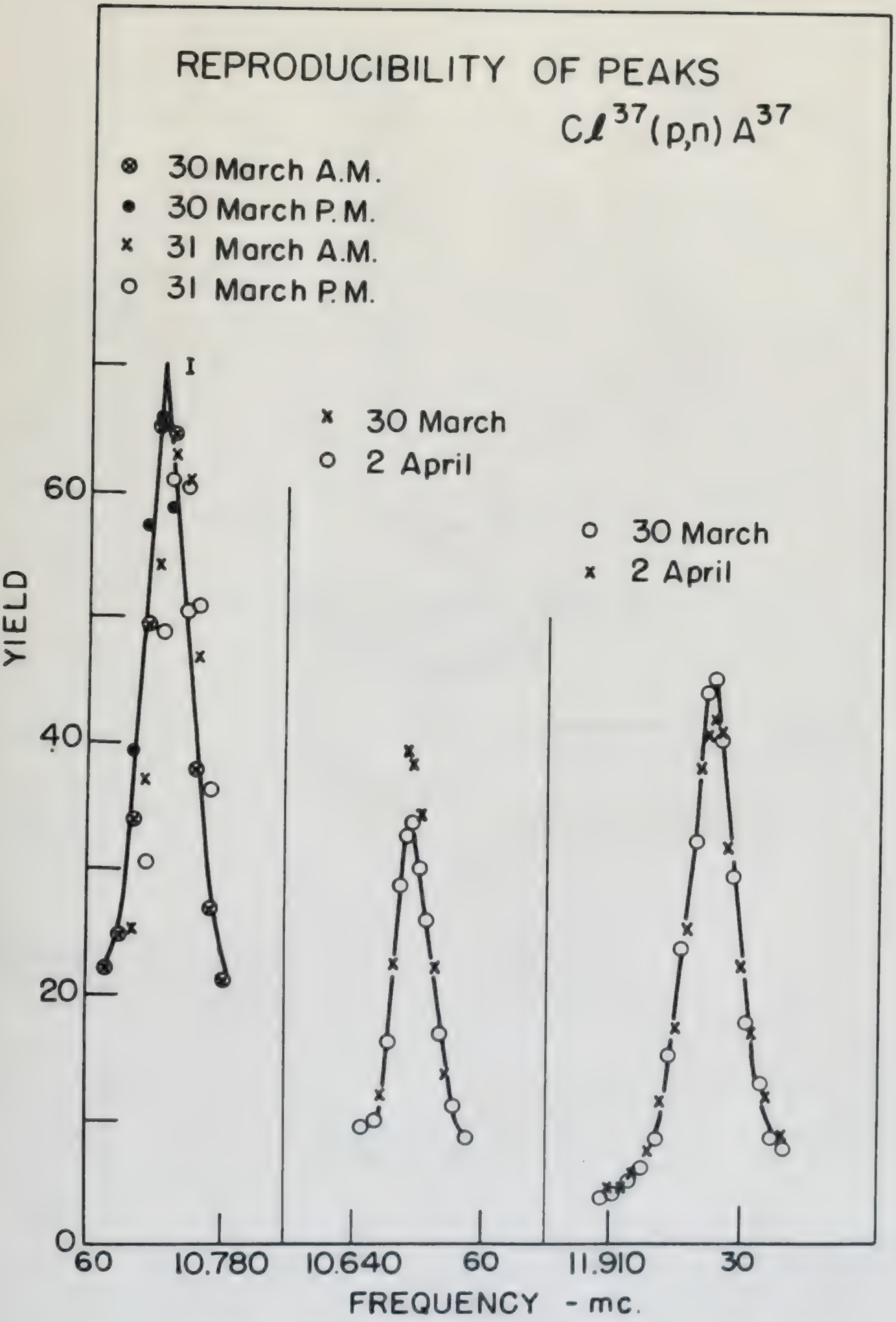
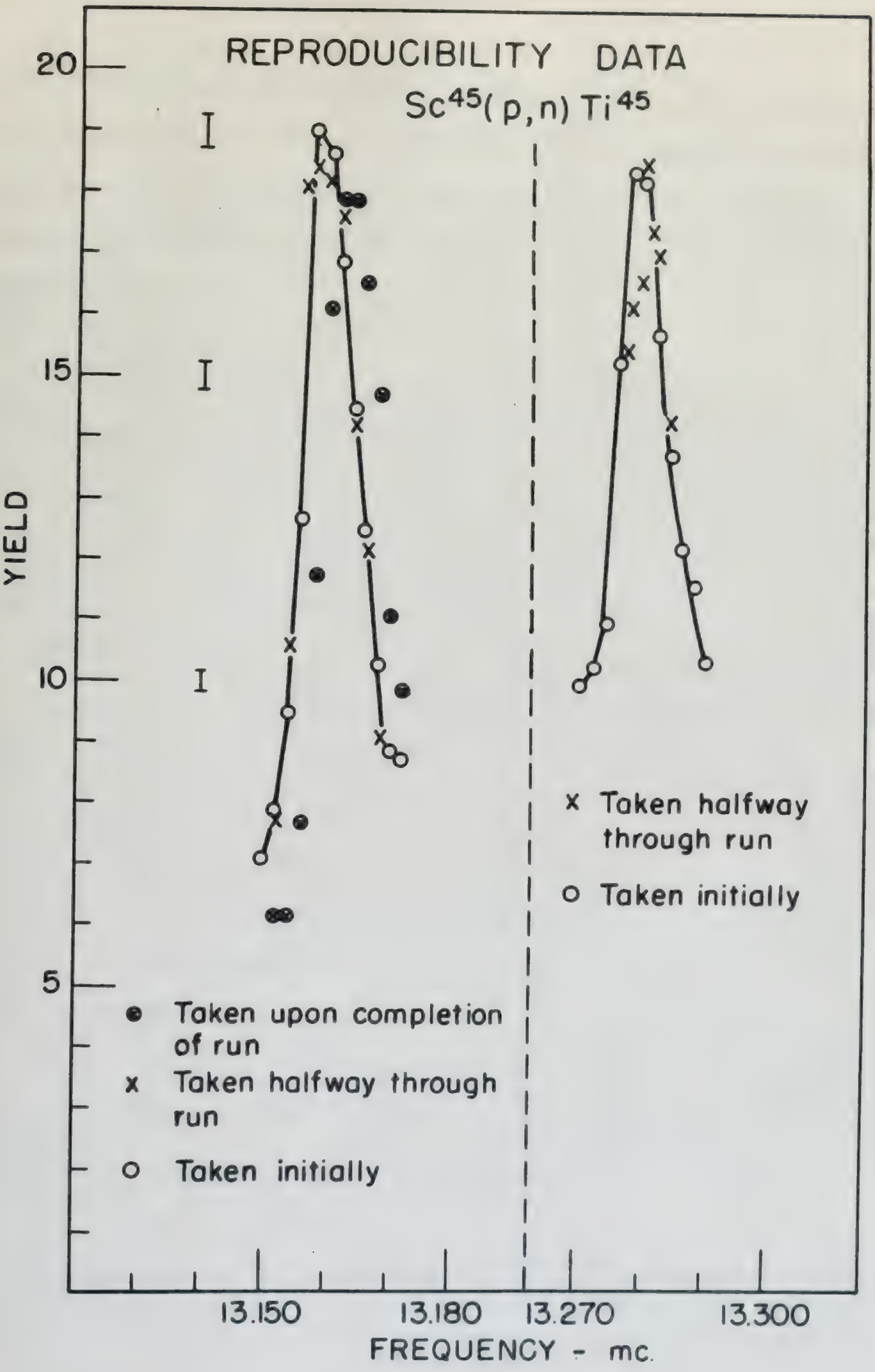

REPRODUCIBILITY OF PEAKS
$Cl^{37}(p,n)A^{37}$
⊗ 30 March A.M.
● 30 March P.M.
× 31 March A.M.
○ 31 March P.M.
× 30 March
○ 2 April
○ 30 March
× 2 April
YIELD
0
20
40
60
60
10.780
10.640
60
11.910
30
FREQUENCY - mc.

Figure 6

REPRODUCIBILITY DATA
$Sc^{45}(p,n)Ti^{45}$


REPRODUCIBILITY DATA
$Sc^{45}(p,n)Ti^{45}$
YIELD
20
15
10
5
13.150
13.180
13.270
13.300
FREQUENCY - mc.
● Taken upon completion of run
x Taken halfway through run
o Taken initially
x Taken halfway through run
o Taken initially

the start and finish of each separate run. It can be seen that the amplitudes and positions of the maxima vary slightly, but the variation in position is much less than the 0.1% mentioned on page 8. The target thickness did not change appreciably.

CHAPTER V

THEORETICAL CONSIDERATIONS

Neutron Energies: The neutron yield from the $Li^7(p,n)Be^7$ reaction is often used as a neutron source. However, there are two disadvantages to the use of these neutrons in some experiments. The lowest energy neutrons obtainable, in the forward direction, just at the threshold, are 29 Kev. In addition, there is a large variation of neutron energy with angle of emission in the laboratory coordinates. For example, at a proton energy of 2.0 Mev, the neutron energy at 0° is 228 Kev, while the energy at 180° is 15 Kev. Willard (W1) tabulates the neutron energies at different angles for a wide range of proton energies.

Since both of these effects are caused by the motion of the compound nucleus, a heavier target nucleus would provide lower energy neutrons in the forward direction at the threshold, and also less variation in neutron energy with angle at all energies.

The following expression for the energy of the neutrons from the $Sc^{45}(p,n)Ti^{45}$ reaction is derived from the laws of conservation of mass-energy and momentum:

$$E_n^{\frac{1}{2}} = \frac{E_p^{\frac{1}{2}}}{46} \cos\theta \pm \left[\left(\frac{44}{46} + \frac{\cos^2\theta}{(46)^2}\right) E_p + \frac{45}{46} Q\right]^{\frac{1}{2}}$$

E_n = neutron energy in Kev.

E_p = proton energy in Kev.

θ = angle of emission of neutrons with respect to direction of incident proton, in laboratory coordinates.

Q = −2850 Kev (see page 23).

From this expression, the energy of the neutrons emerging at threshold (E_p = 2.913 Mev), (θ = 0), is 1.4 Kev. One of the largest neutron yields was obtained with a proton energy of 2.964 Mev. The energy of these neutrons at various angles is given below:

θ	0°	90°	180°
E_n	67.8 Kev	53.4 Kev	34.5 Kev

Thus, it is seen that neutrons from scandium can be obtained at energies as low as 1.4 Kev, compared to the minimum energy of 29 Kev from lithium. For any given energy, neutrons are available from scandium which have less variation in energy with angle than those obtained from lithium. Since the absolute yield of neutrons from scandium was not determined in this experiment, it is not known whether this reaction could be used as a neutron source in work requiring a high flux.

Taschek and Hemmendinger (T2) measured the absolute yield of the $Li^7(p,n)Be^7$ reaction. This required a know-

ledge of the actual target thickness, which was obtained from the "geometric peak." Since scandium is heavier, it is impractical to measure the "geometric peak," and the target thickness must be determined by other means. The upper limit to the target thickness, discussed previously, includes the actual target thickness, the spread in energy of the protons, and the actual width of the energy level.

If one of the peaks were remeasured using a much thinner target, and had a considerably narrower width, then the actual target thickness of the original target would be known to within the width of the thinner target. Thus, if the thicker target had a peak of 5 Kev width, and this peak, when remeasured with a thinner target, had a width of 1 Kev, then the original target thickness would be 5 ± 1 Kev.

A determination of the yield relative to lithium also requires a knowledge of the actual target thickness. However, it is estimated that the neutron yield from scandium is many times less than that obtained from lithium. This estimate is based on an experimental knowledge of the counting rates from the two reactions for different counter geometries.

Energy Levels: In the p,n reaction, a proton of angular momentum $\bar{\ell}$, and spin $\bar{i} = \frac{1}{2}$, bombards a target nucleus of spin $\bar{I}$. The vector channel spin $\bar{s} = \bar{i} + \bar{I}$ combines with the vector angular momentum of the proton ℓ,

to give the spin $\bar{J} = \bar{s} + \bar{\ell}$ of the compound nucleus. Since a proton has an intrinsic even parity, compound nuclei formed from even values of ℓ, will have the same parity as the target nucleus; whereas those formed from odd values of ℓ will have the opposite parity. Mathematically, off-center collisions ($\ell > 0$) can be treated in terms of dead-center collisions, ($\ell = 0$), by adding a fictitious "centrifugal barrier" term which increases rapidly with ℓ. For the energies used in this experiment, it was assumed that the "centrifugal barrier" for $\ell > 1$ was so large that the probability of forming the compound nucleus was small. Thus, ℓ can have the values of 0 or 1. The laws of quantum mechanics permit the following values of J:

For $\ell = 0$; $J = s = I - \frac{1}{2}$ or $I + \frac{1}{2}$, same parity as target.

For $\ell = 1$; $s = I - \frac{1}{2}$, $J = I - 3/2,\ I - \frac{1}{2}$, or $I + \frac{1}{2}$

$s = I + \frac{1}{2}$, $J = I - 1/2,\ I + \frac{1}{2}$, or $I + 3/2$
opposite parity as target.

Non-identical quantum states of the compound nucleus correspond to different energy levels. If the states having the same value of J and ℓ, but different s, are not identical, there will be a separate energy level for each of the eight combinations shown above. If they are identical, these eight combinations result in six different energy levels.

By analogy with spectroscopy, these six or eight related energy states are considered a multiplet, and exist for a given total quantum number. This total quantum number is not defined, but is assumed to be analogous with the orbital quantum number n in atomic theory. From this, it is expected that the multiplet would be repeated as n takes on different values.

On a single particle model of the nucleus, it could be supposed that, just before the emission of a neutron, the compound nucleus could be represented by a wave function describing the neutron moving in the force field of the residual nucleus. This wave function would be characterized by the excitation energy and the coupling of the angular momentum, ℓ , and the spin, i, of the neutron with the residual nucleus. As the p,n reaction is a reversible process, the compound nucleus must have values of J which can be formed not only from a proton and the target, but also from a neutron and the residual nucleus. If the spin of the residual nucleus were known, the other half of the problem could be worked out, and those values of J common to both would be the ones actually observed. However, both of the residual nuclei of this experiment, A^{37} and Ti^{45}, have unknown spins, so that the complete problem cannot be worked out.

If the spacing of the states of a multiplet were small

compared with the spacing between multiplets, groups of six or eight resonance levels might be observed. However, there is a very good chance that states of different multiplets overlap, and also that the single particle picture may not be valid. Preston (P3) discusses the theory of the p,n reaction in detail.

The Sc^{45} nucleus has a spin of 7/2 so that the possible J values of the compound nucleus, Ti^{46}, would be 3 or 4, same parity, and 2, 3, 4, 3, 4, 5, opposite parity. From Figure 4, it can be seen that four of the peaks, at 2964, 3019, 3064, and 3106 Kev, are much larger than any of the other peaks. Also, each of these large peaks has a smaller peak just above it, and a much smaller peak, or an indication of one, just below it. This repeating triplet might indicate that each of the large peaks corresponds to a particular J value being repeated for different total quantum numbers. Between the first two large peaks, there are nine other peaks; between the next two, there are seven; and between the last two, six. The large peaks are occuring closer together at the higher energies, indicating that the multiplet spacing is decreasing. Thus, the observed number of peaks, twenty-five, if assigned to three multiplets, agrees very closely with the theoretical value of eight per multiplet. Table 3 shows the average energy level spacing of

TABLE 3
SPACINGS IN Ti^{46}

Energy of peak at start of interval-Mev.	Energy of peak at end of interval-Mev.	Energy between peaks Kev.	Levels between peaks	Average level spacing
2.964	3.019	55	9	5.5
3.019	3.064	45	7	5.6
3.064	3.106	42	6	6.0
2.964	3.106	142	24	5.7
2.916	3.125	209	34	6.0

Ti^{46}, as observed from the yield curve (Figure 4).

The Cl^{37} nucleus has a spin of 3/2, so that the possible values of J of the compound nucleus, A^{38}, would be 1 or 2, same parity, and 0, 1, 2, 1, 2, or 3, opposite parity. The yield curve (Figure 2) was examined in an attempt to find a similar repeating pattern. Although there were many large peaks, none of them were conspicuously different from the remainder, as was the case in scandium. A number of possible repeating patterns could be picked out from among all of the available peaks. One scheme, using a triplet similar to the one in scandium, gave 128 peaks in 14 multiplets. This doesn't agree with the theoretical value too well, but it is fairly close. Table 4 shows the average energy level spacing of A^{38} based on this scheme. The intervals were taken between the large center peaks of the triplets.

The proton energy for a peak in the yield curve is known to an accuracy of 0.1%, relative to the measured value of the $Li^{7}(p,n)$ threshold, as previously discussed. If these energies were corrected for motion of the center of mass, loss of energy in the target, and displacement of the peak due to the effect of neighboring peaks, the energy levels of the compound nuclei can be obtained by adding the proton binding energy to the corrected proton kinetic energies. The average energy level spacing obtained from the

differences in the energies of the peaks in the yield curves will be accurate, since these corrections will cancel out.

TABLE 4

SPACINGS IN A^{38}

Energy of peak at start of interval-Mev.	Energy of peak at end of interval-Mev.	Energy between peaks Kev.	Levels between peaks	Average level spacing
1.691	1.773	82	10	7.5
1.773	1.819	46	7	5.8
1.819	1.851	32	6	4.6
1.851	1.892	41	8	4.6
1.892	1.942	50	10	4.5
1.942	1.987	45	7	5.6
1.987	2.046	59	7	7.4
2.046	2.095	49	6	7.0
2.095	2.167	72	8	8.0
2.167	2.261	94	11	7.8
2.261	2.325	64	9	6.4
2.325	2.375	50	9	5.0
2.375	2.412	37	8	4.1
2.412	2.463	51	8	5.7
1.691	2.463	772	127	6.0
1.644	2.508	864	140	6.1

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Energy levels in A38 and Ti46 from the p,n reaction on Cl37 and Sc45 respectively

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